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Interactive comment on “Subsidence associated with oil extraction, measured from time-series analysis of Sentinel-1 data: case study of the Patos-Marinza oil field, Albania” *by* Marianne Métois et al.

Anonymous Referee #1

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Review of “ Subsidence associated with oil extraction, measured from time-series analysis of Sentinel-1 data : case study of the Patos-Marinza oil field, Albania” by Metois et al.

The paper provides original data and analyses on ground deformation contemporary to a shallow oil field exploitation.ÂăÂă The paper focusses on the analysis of (2014-2018) surface deformation in the vicinity of the Patis-Marinza oil field, Albania, that operates since 1939. The main result points on an average 15 mm/yr subsidence rate, 2014-2018, above the reservoir zone “where most of the horizontal wells are located”.

Alternatively, crude use of seismological catalogs unbalances the detailed technical analysis for the interferograms. The well-constrained technical results for subsidence are discussed against poor seismicity and production history and without the proper fluid manipulation context, concerning the cited literature (most cited references relate to seismicity driven by wastewater disposal which is not the case in the submitted manuscript).Âă ÂăThe lack of production information and the misused of seismicity catalogs weaken the central message of the manuscript. Most of the discussions on the possible anthropogenic seismicity are flawed in several ways. First, there is no information on how the regional earthquake catalog is built on or selected by merging existing catalogs (USGS and EMSC). Second, the lack of threshold values (i) for selecting an earthquake at a given distance from the reservoir to be a triggered event or a tectonic event and (ii) for a magnitude completeness value over time, prevent any robust analysis of space-time seismicity patterns.Âă From another perspective, the comparison of seismicity and deformation with long term production history is missing. The current 15mm/yr subsidence should drive a more than one-meter subsidence in the past 80 years if sustainable over time. Another possible change point may be used as before-after 2009 when Enhanced Oil Recovery processes started. The one-meter subsidence in the past 80 years should be evidenced locally independent from any detailed instrumental subsidence survey. It will put in context if the current subsidence rate was stable over time or if there is an increase in the recent deformation relatively to past subsidence. These deformation patterns (steady-state or not) are critical parameters for forecasting the future deformation of the area.Âă Furthermore, one advantage of the interferometry analysis is the ability, by the same tools, to sample a large area. Accordingly one would expect the authors to take advantage of the several oil and gas fields that are located in this area (see fig. 4) to calibrate and validate the surface deformation and seismicity related to these different hydrocarbon production sites.Âă Accordingly, I recommend the paper to be deeply reconstructed. For one option, the authors may focus on the interrelationships between subsidence and regional hydrocarbon extraction on different sites. To investigate the possible relationship between seismicity and hydrocarbon production in this zone, it requests new and robust inputs for the seismic analyses.Âă Other technical comments and suggestions are listed below.

Specific comments :Âă

oil field operations: - In several places in the manuscript (including the abstract) the authors point on the subsidence bowl to be centered above the area where horizontal production wells are located. There is neither discussion nor reference to support why horizontal production wells should increase the subsidence. We can find in existing reports (not cited in the manuscript) a one order magnitude change in production rate on that period. Such a more quantitative information should be discussed in the context of subsidence rate change over time.Âă - In the introduction, it is difficult to understand why the 2008 reactivation of the field may enhance the local seismicity so far away from the 1939 onset time of production. I suggest the authors summarise comprehensively the history of production that is missing in the manuscript. There is information available in open access reports that should be listed in the manuscript, e.g., "the 6% of reserve being produced during the 1939-1990 period, Weatherill et al. 2005 SPEÂăhttps://doi.org/10.2118/97992-MS"; and "The Patos Marinza oilfield peak production during this period was 15,000 bbl/day in 1975 but due to a lack of maintenance, reduction in drilling activity, and lack of new technology the oilfield declined to producing almost nothing in the 1990's and it appeared to be on its last legs. Since 2008, a new Canadian owner has drilled more than 600 horizontal wells and has also implemented enhanced oil programs which have pushed the production to 21,000 bbl/day which is significantly higher than any time in the oilfields history" (Delmaide, 2017)";ÂăÂă - Also, it appears there are problems with how the oil reservoirs are described in the paper (100m-2 km depth) when the available literature points on "Measured drilling depths are typically 2,500 meters, with 500- to 700-meter horizontal legs." (e.g., Mazerov, 2011). Also, Weatherill et al. (2005) report on "The two separate fields (Patos in the south and Marinza in the north) have productive sands at differ-

ent depths, i.e., 0 - 1200 m for Patos and 1200 - 1800 m for MA". These differences are not discussed in the manuscript.Âă - Hydrocarbon field locations and numbers for other nearby oil-gas reservoirs do not overlap with other existing maps (e.g., Mezini and Musai, 2012, Velaj SPE, 2015). Information for location and site references are welcome.Âă - The contour for the zone of intense extraction should appear on fig3a to be able to describe how it overlaps with the contoured types of production stimulations

seismicity: Abstract: "the increase of background seismicity": Usually, for seismology community the background seismicity is related to the steady-state tectonic event rate; here we do not know how field operations can increase the background seismicity because there is no analyze to either define or to quantify the seismicity before or far-field from the oil extraction onset or oil reservoir, respectively. l3,vp5: "In 2013, three Mw$\sim$4 earthquakes that occurred in the area alarmed the population". The distances to the oil field reservoir are not described for the 3 events. Furthermore, it is difficult to read who are these events in the figure (3a) where most of the 2013 events are far outside the reservoir contour. Again the description of the rules to accept or to reject the seismic event to be anthropogenic or tectonics is not explicitly described in the manuscript.ÂăÂă - seismicity catalogs: the only information on the seismicity database is provided in figure 3 caption. "CSEM-EMSC; USGS, before and after 2004, respectively". However, using the USGS catalog after 2004 (as downloaded Sept2019), the date and magnitude of the M4+ event in late 2016, that is attributed to the oil field extraction, does not exist on the USGS database even as M2.5+ event? - the significant M4.8 event of figure 3a does not emerge on figure3b using seismic moment value, whereas it is one of the most significant events in this selected time-space window?Âă

subsidence: - Figure 4: what does mean "oil field (2010) contour "on this figure is not defined.Âă - the oil field contour on fig 3 does not match the other figures? - Strong subsidence is located close to the north-western Balla Divjaka gas field, and it is not discussed in the text. -l25-30,p13: "Both ascending and descending velocities are well reproduced by a 1045 m-long and 632 m-wide reservoirs located at a depth of $\sim$1.6

km under the zone of maximum subsidence". We will appreciate error bars on the meter accuracies of the equivalent reservoir dimensions. Also, if these values are not a-priori imposed, we need to know which ranges were tested for length, width, thickness during parameter tuning of the model. If not, we do not understand what the key outputs of the model are?âĂÍ earthquake triggering and Patos-Marinza fluid manipulations: - l10,p2: "Furthermore, drilling processes and fluid extraction can change the pore pressure and stress field in the mediumÂăso muchÂăthat anomalous seismic activity may be triggered". This point is out of context in the case of seismicity triggered by oil and gas recovery. One of the main lessons of anthropogenic seismicity related to hydrocarbon recovery is that earthquakes are triggered by small stress change, i.e., a few 0.1-01 MPa, the same order of magnitude of stress change than the ones that trigger aftershocks (e.g., for a review Foulger et al. 2018)Âă -l15,p2: "For instance, the seismicity observed in the Oklahoma oil and gas field and its relationship with wastewater disposal has been extensively studied in the last years (Murray, 2013; Walsh and Zoback, 2015". Here there is a problem because the authors use examples of wastewater injections, that is not similar to enhanced recovery technique, to support the triggering potency of enhanced recovery.Âă - Because no threshold for magnitude completeness is used, the analysis of seismicity patterns over space and in relation to subsidence and production are not robust. Any evidence for an increase in seismicity rate has to be tested not to be biased by a change in the earthquake recording thresholds (e.g.,ÂăJ Woessner,ÂăS WiemerÂă- Bulletin of the Seismological . . ., 2005). The lack of Mmin choice induces biases in seismicity rate changes as driven by change is instrumental network geometry. For all standard seismological studies, the regional choice for Mmin is derived from the frequency-size distribution of earthquakes. ÂăFor the anthropogenic event selection, a proper way to define anthropogenic seismicity at a given reservoir distance is to map different distance ranges and to extract up to which distance the seismicity differs from the background tectonic rate. As an example using the USGS database 1973-2018, M>=4 or M2.5, there is no evidence for earthquake clustering in the vicinity of the oil field (figure R1-2)?Âă - Most of the cited literature

relates to the case for wastewater injection (or gas withdrawal). There is no evidence for the wastewater injection to drive seismicity in this oil field. In the case of the shallow oil field, the initial pressure allows for smaller pressure drop than for gas fields, and it may be the reason why there is four times less reported cases for earthquake triggered by oil rather than gas extraction, respectively (e.g., for a review Foulger et al. 2018). A section that compares subsidence around the Patos-Marinza oil fields with other cases where oil extraction triggered subsidence and seismicity is missing.Âă As example l20, p16 "Such type of surface deformation is likely associated with stress changes in the neighbouring geological formations, which have been correlated with low to intermediate magnitude seismicity in several well-instrumented oil fields (e.g. Segall et al., 1994; Ellsworth, 2013; Keranen et al., 2013, 2014; Hornbach et al., 2016)." These four references are cited to support surface deformation and in-depth stress changes induced by oil recovery., but they are all out of context. Segall et al. 1994, reports on a 4-5 km depth, 65 MPa initial pressure, the gas field associated with a few cm subsidence cases, M4 seismicity. Ellsworth 2013 review paper and Keranen et al., 2013 and Hornbach et al., 2016 papers for Oklahoma and texas respectively, all the three reports entitled "Injection-induced earthquakes", do not describe any subsidence data or extraction value, and focus on wastewater injection below reservoirs for which no data are available on the case study of Patos-Marinza fluid manipulation.Âă

Figure R1: Seismicity map around the Patos-Marinza oil fields. M>=4 earthquake, 1973-2019, from USGS catalogue. Black box is the schematic contour of the Patos and Mazrinza oil-fields. (annex)

Figure R2: Seismicity map around the Patos-Marinza oil fields. M>=2.5 earthquake, 1973-2019, from USGS catalogue. Black box is the schematic contour of the Patos and Mazrinza oil-fields. (annex)

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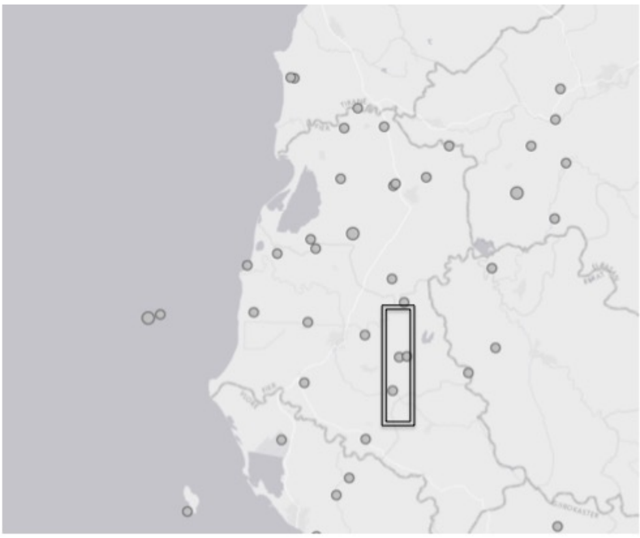

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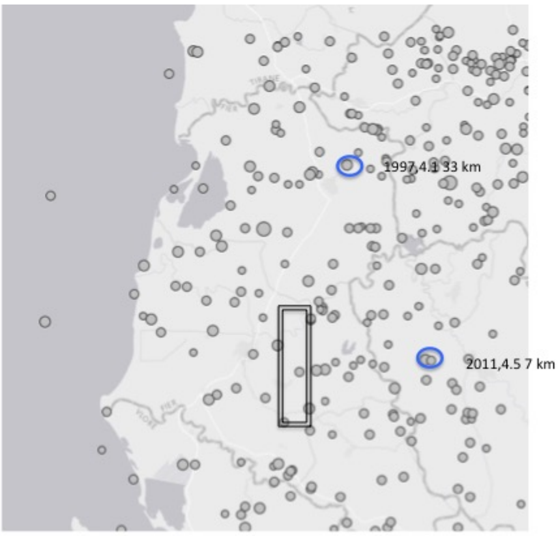

Fig. 2. Figure R2: Seismicity map around the Patos-Marinza oil fields. M>=2.5 earthquake, 1973-2019, from USGS catalogue. Black box is the schematic contour of the Patos and Mazrinza oil-fields.